ISSN 2321-807X
Volume 13 Number11
Journal of Advances in chemistry

Mechaical Properties of Randomly Oriented Calotropis Gigantea Fiber-Reinforced Phenol Formaldehyde Biocomposites

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ABSTRACT

Mechanical properties such as tensile, flexural and impact, of randomly oriented *Calotropis Gigantea* Fiber (CGF) -reinforced Phenol Formaldehyde (PF) biocomposites were studied based on the five different fiber loadings (10, 20, 30, 40, and 50 vol%) and three different fiber lengths (3, 9, and 15 mm). The critical fiber length and optimum fiber loading were identified with the maximum level of mechanical properties in this composite. The fractured surfaces of composites after testing were studied by scanning electron microscope (SEM). The results revealed that the addition of CGFs is improving the mechanical properties of the PF composite. The properties of composites reach the properties of the neat resin sample at 20 vol% of all the cases. The critical fiber length and the optimum fiber loading to obtain the maximum mechanical properties were identified as 9 mm and 40 vol% respectively. Experimental tensile property values were compared with theoretical values and found to be in good agreement.

Indexing terms/Keywords

Natural fiber, Biocomposite, Mechanical properties, Theoretical models, Scanning electron microscope

Academic Discipline And Sub-Disciplines

Polymer Engineering and Technology, Engineering Materials, and Mechanical Engineering

SUBJECT CLASSIFICATION

Polymer and material analysis, Mechanical properties, and Effects of fiber length and content

TYPE (METHOD/APPROACH)

Experimental analysis

1. INTRODUCTION

In the recent years a wide range of natural cellulose fibrous materials found to be a suitable alternative for man-made synthetic fibers such as carbon, glass and aramid, in polymer matrix composites because the synthetic fibers are causing environmental pollution duet to the non-degradability and absorbing more energy for their preparation. Therefore, natural cellulose fibers receive greater attention and also attraction from the manufacturer (automotive industry and construction industry), material engineers, scientist and research community, due to their light weight, higher specific properties, renewability, biodegradability and non toxic. Many researchers have been carried out the extensive studies on the preparation and properties of polymer composite filled with various natural cellulose fibers[1, 2]. The demand for new fiber materials with better properties to be used in various fields of applications such as automobile, electronics and structural are growing which led to the development of better polymer composites. The polymer composites reinforced with better reinforcement agents can provide, the better physical and mechanical properties[3].

Among the various plants based natural cellulose fibers, CG, a family of the *Asclepiadaceae,* is a traditional medicinal plant with unique properties which yields a durable fiber (Bowstring of India) useful for ropes, carpets, fishing nets, and sewing thread. From pre-historic times, these plants are conserved as genetic resource and also used as fodder, food and fiber. The CG plants grow very well in any soil and environmental conditions without any cultivation practices. They have many different parts like, stem, root, leaves, flowers, fruit, seeds, and the silky hairs of seeds, with immense potential to cure a variety of human and animal diseases and also disorders[4]. The whole plant is used for biogas and as a substitute for petroleum products. It is a highly potential plant resource for the fiber production from the bark and the silky hairs from its seeds[5]. These plants are doing an extraordinary work of pollution monitoring in the place[6]. The feasibility of two kinds of CGFs, namely bark and seed fibers, as a promising alternative raw fiber material for fiber-reinforced composite was evaluated[7]. CGFs have comparatively same structural nature like other stem fibers such as, banana and roselle. The chemical structure is also comparable with the banana and roselle fibers. Less work has been reported on the mechanical properties of CGF-reinforced polymer composites. In the present investigation, a new series of polymer composites consists of the CGFs and the PF resin were prepared using hand lay-up technique and characterized based on the mechanical properties such as tensile, flexural and impact. Composites were prepared by five different fiber loadings and

DOI :10.24297/jac.v13i11.5910
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the three different fiber lengths with the aim of finding the critical fiber length and optimum fiber loading to obtain the maximum mechanical properties. The fractured surfaces of composite materials after mechanical testing were examined by SEM. Experimental tensile property values were compared with theoretically predicted values.

2. EXPERIMENTAL DETAILS

2.1 Materials

The CGFs were extracted from the stem of the plant manually and cut into three different lengths 3, 9 and 15 mm for the use as a reinforcement agent for phenol formaldehyde resin matrix. The resole type Phenol Formaldehyde (PF) liquid resin with the density of 1.3 g/cm^3 and specific gravity of 1.14 was used as a polymer matrix with the cross-linking agent (v) and acidic catalyst (hydrochloric acid). All the chemicals are procured from the POOJA Chemicals, Madurai, Tamilnadu, India.

2.2 Extraction of the CGFs

The CGFs were extracted from the bark or stem of the CG plant. The stems were tied into bundles using bags and retted in tanks containing water for 2-3 days to ensure the easy removal of fibers without any damage from the stem. The fibers were removed from the stems manually and cleaned and dried in the sunlight for 1 day. Figure 1 shows the various parts of the CG plant. The chemical composition and typical properties of the CGF is presented in Table 1. The CGFs are light grey[7] in color with the length of 0.5 m and their shape varies from fiber to fiber, and also non uniform. Fiber thickness varied from 0.11 mm to 0.83 mm which is measured using a Digital microscope.

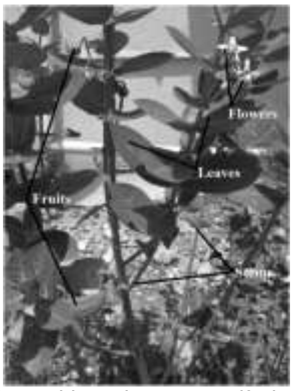


Figure 1. Digital image of CG plant with various parts (fruit, stems, flowers and leaves)

Table 1 Chemical composition and typical properties of the CGFs[7]

Chemical composition (%)		Typical properties	
Holocellulose	76	Appearance	Light grey
Cellulose	57	Tensile strength	381 MPa
Lignin	18	Strain at break	2.1 %
Alkali soluble substance	17	Young's modulus	9.7 GPa
		Density	0.56 g/cm^3

2.3. Preparation of composites

A hand lay-up technique with a mould box with the size of 150 × 150 × 3 mm was used to prepare the composite plates. First, the mould box was coated with a releasing agent for the easy removal of the cured composite plates. The cross-linking agent (v) and acidic catalyst (hydrochloric acid) were mixed with PF resin in the ratio of 2:1.5:100 using mechanical stirrer. After stirring for 30 minutes, the resin mixture was poured into the mould containing the CGFs, where the fibers are randomly distributed. Then, the mould was closed under pressure and allowed to cure at room temperature for 24 hours

2.4. Mechanical testing

For mechanical tests, specimens were cut from the prepared composite plates as per the ASTM standards. The tensile tests were performed according to ASTM D 638-10 using an FIE universal testing machine at a crosshead speed of 2 mm/min. The flexural tests were conducted on the same machine according to ASTM D 790-10 with the crosshead speed of 2 mm/min. Impact test for composite specimens was performed on Izod impact machine according to ISO 180. Totally, five specimens were tested for each combination to obtain the average value.

2.5. Fractographic study

The microstructure of the fracture surface of composite specimens after mechanical tests was taken by Scanning Electron Microscope (HITACHI N-3000S) and examined to identify the mode of failure.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of composites having the fiber length of 3 mm

Tensile properties

The variations of average tensile properties of the CGF/PF composite having fiber length of 3mm were measured based on the five different fiber loading and presented in Figs. 2a-2c. From the Fig.2a, it is clearly observed that the tensile strength of composite increase with the increase in fiber loading. Composite reaches the tensile strength of the neat resin sample at 20 vol%. The addition of the CGF at a 10 vol% decrease the tensile strength of the PF composite, which may be by improper transmission of applied load to the CG fibers due to the dispersion of the CG fibers. It shows that the sole reinforcing effect of the CGFs to the PF is not properly served at 10 vol% of the CGFs. Furthermore, when the CGFs have increased from 10 vol%, the tensile strength of the CGF/PF composite also increases. At 40 vol % of the CGF, the composite shows the maximum tensile strength of 35.26 MPa which 22.76% higher than the neat resin sample. This is may be due to the better interfacial bonding between the fibers and the matrix and also due to the proper load sharing between them. The further addition of the CGFs (50 vol%) decreases the tensile strength of composite. This is due to the poor wettability between the fibers and the matrix, i.e., brittleness of composite increases. Moreover, it can be identified that the percentage increments from the one fiber loading to the other fiber loading i.e., from 20 to 30 vol% and 30 to 40 vol%, is small. The probable reason is that the end points of fibers are more due to the short length of the fibers. It means that there is an insufficient fiber length to transmit the applied load.

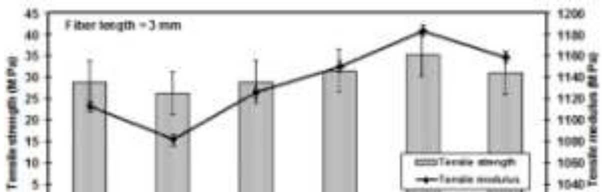
Figure 2a also shows the tensile modulus of the CGF/PF composite plotted against the percentage of fiber loading. It shows that composite reaches the tensile modulus of the neat resin sample at 20 vol%. The tensile modulus was also increased up to 40 vol% and then dropped like tensile strength. An improvement of 6.39% was obtained at the tensile modulus of 40 vol% composite, when compared with the neat resin sample.

Flexural properties

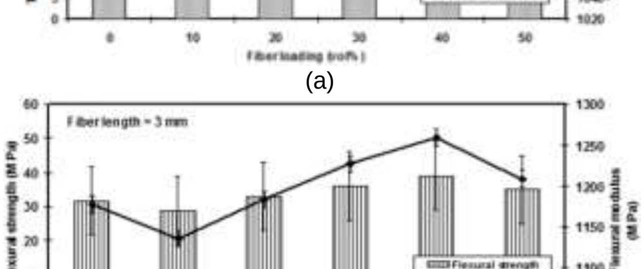
Figure 2b shows the variations of the flexural properties, flexural strength and modulus, of CGF/PF composites containing various loadings of the CGFs. The values of flexural strength increased upon increasing the loading of the CGFs in the composites. The flexural strength decreased with the initial addition of the CGFs and then increased with the further addition of the CGFs. At 20 vol%, composite reaches the flexural strength of the neat resin sample. The maximum flexural strength was obtained in 40 vol%, which is 23.09% higher than the neat resin sample and 36.1% higher than 10 vol% composite. It can also be seen that the flexural strength of 50 vol% composite is lower than that of 30 vol% composite. At 50 vol%, the sufficient cross-linking density cannot be attained due to the higher percentage of fiber loading, whereas at 40 vol% composite, the sufficient cross-linking density can attain due to the required percentage of fiber loadings. The percentage of increment from one fiber loading to the other fiber loading is also small like in tensile strength. It is may be due to the insufficient fiber length in the composites. The variations of flexural modulus of composite are also shown in Fig. 3b. The flexural modulus values of composite increased with the addition of the CGFs and reached the flexural strength of the neat resin sample at 20 vol%. Here also, the flexural modulus values are increased up to 40 vol% and then dropped. It is due to the better bonding between the fiber and the matrix at 40 vol% composite. A 6.95% of the improvement was attained at flexural modulus of 40 vol% composite when compared with the neat resin sample.

Impact strength

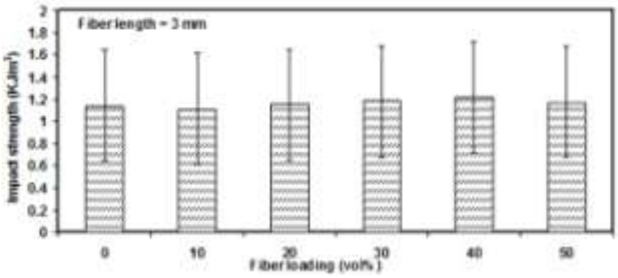
The results of the impact tests for the CGF/PF composites at various fiber loadings are given in Fig. 2c. It can be observed that the impact strength decreased to 1.11 KJ/m^2 at a CGF loading of 10 vol%, but increased to 1.15 KJ/m^2 at a CGF loading of 20 vol%. It shows that the addition of the CGFs to the PF influences the impact strength of the PF composite from 20 vol%. The maximum impact strength was attained at 40 vol% of the CGFs, which is 7.02% higher than the neat resin sample. The value of impact strength was decreased at 50 vol% of the CGFs. It is may be due to the poor wettability between the fibers and the matrix.



(a)



(b)



(c)

Figure 2. Variations of mechanical properties: (a) tensile properties, (b) flexural properties, and (c) impact strength of the CGF/PF composite prepared with the fiber length of 3 mm for various fiber loadings

3.2 Mechanical properties of composites having the fiber length of 9 mm

Tensile properties

Figure 3 shows the measured tensile properties of the CGF/PF composite according to the different fiber loading. The tensile strength of the neat resin sample was reached by the composite with the fiber loading of 20 vol%. The addition of the initial stage of fiber loading decreases the tensile strength of the composite by 4.01% when compared with the neat resin sample, but the further addition increases the tensile strength of composite by 14.43%. The tensile strength of composite increased continuously from 20 vol% to 40 vol% and then decreased at 50 vol%. The wettability at the 50 vol% composite is comparatively lower than the composite having the fiber loading of 40 vol% which is due to the weaker composite specimens. It means that at 40 vol% composite, the matrix wets the fibers in a sufficient manner, whereas at 50 vol% composite, the matrix is insufficient to the effective wettability of the fibers. When comparing the 40 vol% composite and the neat resin sample, a 61.57% of increment was attained at 40 vol% composite. Furthermore, the percentage increments from one fiber loading to the other fiber loading was higher when compared to the composites having the fiber length of 3 mm for all the fiber loadings. Moreover, 40 vol% composite at the fiber length of 3 mm shows the low tensile strength compared to the 40 vol% composite at the fiber length of 9 mm. The probable reason is that the applied load is properly transmitted to the fibers through the matrix, i.e., proper load sharing between the fibers and the matrix. The fiber length of 9 mm may be sufficient for proper load sharing with the better interfacial adhesion through effective wettability.

The tensile modulus of composite for different fiber loadings is also illustrated in Fig. 3a. The tensile modulus was increased with the increasing of loading of the CGFs. However, it was decreased when the fiber loading was increased up to 50 vol%. It might the high percentage of fiber loading could not wetted by the resin matrix, which results in quick failure of composite with the reduced modulus value. The maximum tensile modulus of 1231.9 MPa was observed at 40 vol%. The tensile modulus values of composite with the fiber length of 3 mm and the fiber loading of 40 vol% were also high compared to the 40 vol% composite at 9 mm.

Flexural properties

The results of the flexural test carried out on the CGF/PF composites according to the different fiber loading were shown in Fig. 3b. The lowest flexural strength was observed at the composite due to the initial addition of 10 vol% of the CGFs. The flexural strength increases with the further addition of the CGFs from 20 vol%. However, the flexural strength of composite decreased after addition of the CGFs from 40 vol% to 50 vol%. This is due to the incompatibility between the fibers and the matrix due to the poor wetting of fibers by the matrix, which leads to the reduction in the composite strength. Here also, the flexural strengths of composite prepared with the fiber length of 3 mm are lower than the composite prepared with the fiber length of 9 mm. The proper load sharing with the sufficient fiber length is responsible for this higher range of flexural strength. The flexural modulus values obtained after three point bending flexural tests were also shown in Fig. 3b. The flexural modulus values also increased from 20 vol% to 40 vol% and then dropped. This is may be due to the fiber-to-fiber interaction by the insufficiency of the resin matrix to wet the fibers. It increases the brittleness of the composite which leads to the sudden failure of the composite specimen. It means that there is an insufficient resin matrix for load sharing.

Impact strength

Figure 3c presented the impact strength results of the CGF/PF composites for the different fiber loading. Composite prepared with 10 vol% of the CGFs displayed low impact strength compared to the neat resin sample. It may due to the fact that even though there is a sufficient fiber length, insufficient fiber dispersion is occurring for the load sharing. The impact strength increased from 20 vol% to 40 vol% and then dropped. Therefore, 40 vol% composite showed the highest impact strength (1.27 KJ/m^2). The impact strength value of 50 vol% composite was lower than the 30 vol% composite. This is may be due to the poor interaction between the fibers and the matrix by the insufficient matrix for the wetting of the fibers, resulting in reduction of composite strength at higher fiber loading. The impact strength values of composite having the fiber length of 9 mm are superior compared to the composite prepared with the fiber length of 3 mm.

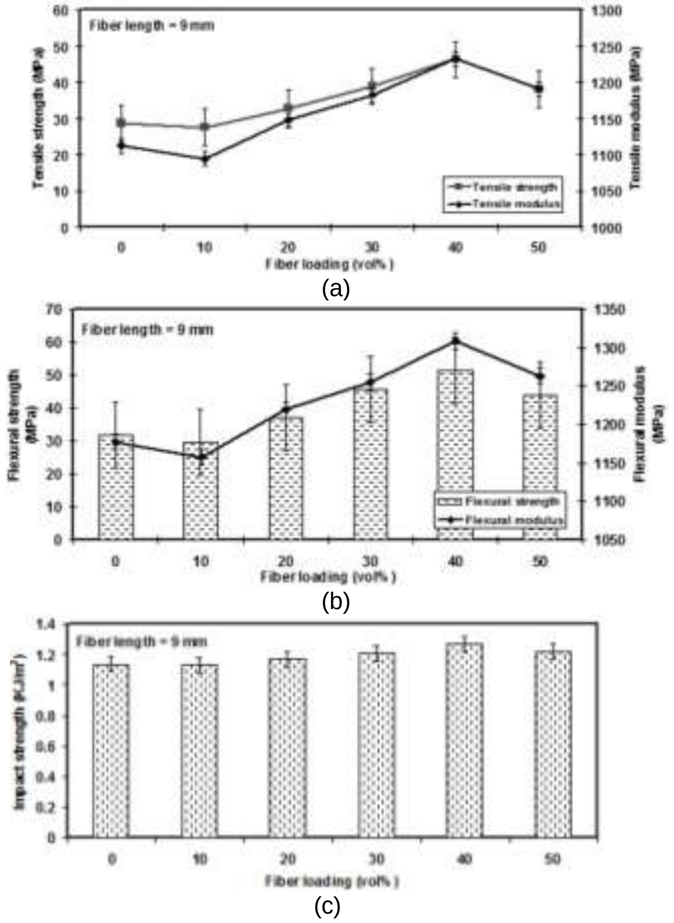


Figure 3. Variations of mechanical properties: (a) tensile properties, (b) flexural properties, and (c) impact strength of the CGF/PF composite prepared with the fiber length of 9 mm for various fiber loadings.

3.3 Mechanical properties of composites having the fiber length of 15 mm

Table 2 lists the mechanical properties, including tensile, flexural and impact, of the CGF/PF composite containing the different loading of the CGFs. From the Table 2, it is inferred that the tensile strength is higher at the fiber loading of 30 vol% than at 40 and 50 vol%. The probable reason is that the higher fiber length with the highest fiber loading creates the improper fiber wetting by the matrix due to the increased fiber entanglement. Moreover, there is a possibility of formation of the fiber or the matrix- rich areas within the composite specimens due to the higher fiber length. Due to this, the strength of the composite prepared with longer fiber length and the higher fiber loading was reduced[8]. An improvement of 21.57% was attained at 30 vol% composite when compared with the neat resin sample. The tensile modulus of the CGF/PF composite for the various fiber loadings is also given in Table 2. The tensile modulus of composite reached the neat resin sample at 20 vol%. Composite attains the maximum value of tensile modulus at 30 vol% and then the tensile modulus values decreased. The tensile strength and modulus value of 40 vol% composite with the fiber length of 9 mm were higher than the 30 vol% composite with the fiber length of 15 mm. Moreover, when compared to the 40 vol% composite having the fiber length 3 mm, the 30 vol% composite with the fiber length of 15 mm shows the lower value of tensile strength and modulus.

The flexural properties of the CGF/PF composite after three pint flexural tests for varying fiber loading are illustrated in Table 2. It can be seen that the flexural properties are also increased up to 30 vol% and then dropped at 40 and 50 vol%. This is also the reason of longer fiber length with the highest fiber loading, which results in formation of fiber bending at a particular location within the composite. It does not contribute for wetting with the matrix. Therefore, the strength of the composite was reduced. The flexural properties of 30 vol% were also lower than the 40 vol% composite with 3 mm fiber length and the 40 vol% composite with 9 mm fiber length.

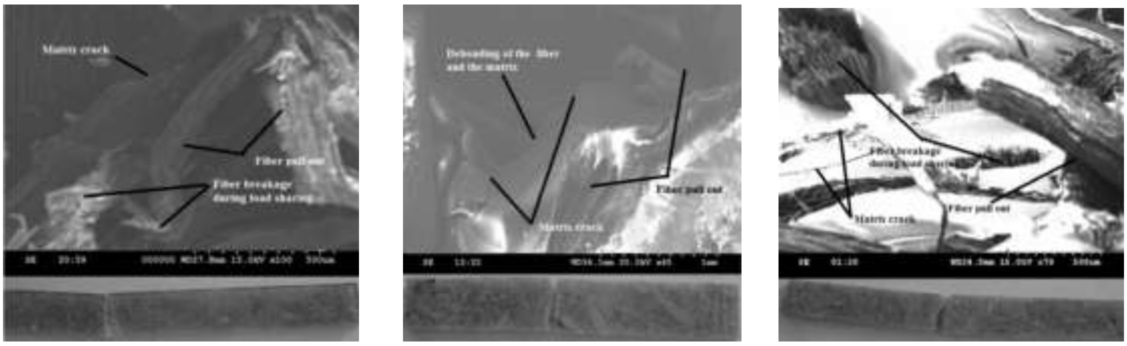
The impact strength of composite was increased with the increase of fiber loading up to 40 vol% and then dropped at 50 vol%, as given in Table 2. The impact strength of the neat resin sample was reached by the composite at 20 vol%. The maximum impact strength was obtained in 40 vol%. 50 vol% composite shows the impact strength of 1.18 KJ/m^2, which is 1.69% lower than the 40 vol% composite. From the impact tests, it is clearly observed that the energy required to fracture composite specimens (40 vol%) is higher than the 50 vol% composite. It is due to the better interfacial bonding between the fiber and the matrix and the better cross-linked systems. Due to the better cross-linked system, failure occurs in brittle nature, which depends on both crack initiation and crack propagation within the composite specimens during the test. The stresses are concentrated due to the crack initiation and propagation, which are more sensitive to interfacial adhesion between the fiber and the matrix. The impact strength of 40 vol% composite with the fiber length of 9 mm was maximum than the 40 vol% composite prepared with the 15 mm fiber length. This is may be due to the fiber entanglement by longer fiber length within the composite.

Table 2 Average mechanical properties of CGF/PF composite prepared with the fiber length of 15 mm along with standard deviation.

Fiber length (mm)	Fiber loading (vol%)	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (KJ/m^2)
0	0	28.7±2.4	1112.4±22.2	31.70±5.7	1177.4±32.9	1.14±0.18
15	10	27.81±2.1	1088.5±40.1	30.41±1.5	1128.2±34.1	1.13±0.15
	20	31.75±2.8	1114.1±27.1	33.92±5.1	1180.5±40.7	1.15±0.13
	30	34.89±3.7	1178.4±23.8	38.33±3.1	1225.4±35.9	1.19±0.14
	40	32.03±2.1	1151.8±25.8	35.82±4.4	1206.9±47.0	1.20±0.17
	50	28.42±2.5	1137.5±21.9	30.53±2.7	1160.7±27.9	1.18±0.14

3.4 SEM Studies on the fracture surfaces of composite specimens

The fracture surfaces of composite samples were examined by SEM and it showed the both the fiber breakage and fiber pull-out, which indicates a better interfacial adhesion between the fiber and the matrix. Figure 4a shows the fracture surface of the CGF/PF composite with the 40 vol% of fiber loading and 9 mm of fiber length after tensile test, in which fair adhesion is confirmed by the presence of fiber pull-out and gaps between the fibers and the matrix. The fracture surface of the CGF/PF composite (40 vol% and 9 mm) after flexural test is shown in Fig. 4b, which also shows the fiber breakage and the matrix due to the pull-out. It conforms to the strong interaction between the fiber and the matrix. Figure 4c shows the fracture surface of the composite specimen (40 vol% and 9 mm). It can be seen that the fiber breakages are more and became dominant, which confirms the strong adhesion between the fiber and the matrix. Therefore, the SEM studies confirm the better interfacial bonding between the fiber and the matrix at 40 vol% of fiber loading and 9 mm fiber length.



(a) (b) (c)

Figure 4. SEM images of fracture surfaces of the CGF/PF composite (9 mm and 40 vol%): (a) tensile test, (b) flexural test, and (c) impact test

3.5 Theoretical modeling of tensile properties

Natural cellulose fiber-reinforced polymer composites are frequently prepared due to the fast and efficient development of moulding methods adopted from the composite industry. The strength and stiffness are the most important parameters to understand the behaviors of natural cellulose fiber-reinforced polymer composites. These parameters of composite are predicted by a number of theoretical models[9, 10]. Several attempts have been taken by several authors to predict the tensile properties of fiber-reinforced polymer composites theoretically. The most widely used theoretical models are: Hirsch's model, Series model, Parallel model, Modified Bowyer and Badar's model, modified rule of the mixture model. In this study, the Hirsch's model, Series model, and modified Bowyer and Bader's model are to be used to predict the tensile strength and modulus of the CGF/PF composite prepared with the fiber length of 9 mm. According to the Series model[11], the theoretical tensile properties can be predicted by the following equations:

$$M_c = \frac{M_m \times M_f}{M_m \times V_f + M_f \times V_m} \tag{1}$$

$$T_c = \frac{T_m \times T_f}{T_m \times V_f + T_f \times V_m} \tag{2}$$

where T_f, T_m and T_c are the tensile strength of the fiber, matrix and composite respectively. M_f, M_m and M_c are the tensile modulus of the fiber, matrix and composite respectively. According to the Hirsch model[11], the equation for the prediction of tensile modulus is expressed as:

$$M_c = e\left(M_f \times V_f + M_m \times V_m\right) + (1-e)\frac{M_f \times V_m}{M_f \times V_m + M_m \times V_f} \quad (3)$$

The equation for the prediction of tensile strength is expressed as:

$$T_c = e\left(T_f \times V_f + T_m \times V_m\right) + (1-e)\frac{T_f \times T_m}{T_f \times V_m + T_m \times V_f} \quad (4)$$

where e is a parameter and its value depend on the sharing of applied load between the fiber and the matrix, i.e., stress transfer between the fibers and the matrix. According to modified Bowyer and Badar's model[11], the tensile modulus is predicted using the following equation:

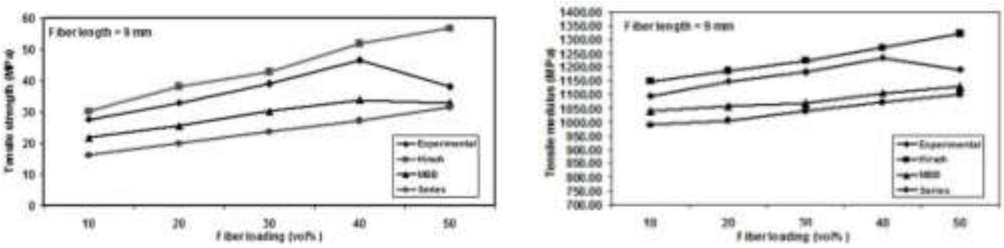
$$M_c = a_v \times M_f \times V_f + M_m \times V_m \quad (5)$$

$$T_c = a_v \times T_f \times V_f + T_m \times V_m \quad (6)$$

where $a_v = k_1 \times k_2$ is the overall reinforcing factor. k_1 is the fiber orientation factor and k_2 is the fiber length factor.

Figures 5a and 5b compare the theoretically predicted tensile modulus and strength values by various theoretical models with the experimental values at different fiber loading respectively. From Fig. 5a, it is clearly observed that the tensile strength values predicted by the Hirsch's model are very close to the experimental tensile strength values. In both the equations of Hirsch's model, the value of constant parameter *a* is 0.51 to obtain the good agreement between the predicted and experimental tensile strength and modulus values. MBB and Series models predict the tensile strength values, which are lower than the experimental tensile strength values. The values of k_1 and k_2 in the MBB equations were found to be 1 and 0.45 to obtain a good agreement with experimental values. It is already observed experimentally that the tensile strength values of composite prepared with the 9 mm of fiber length are increased up to 40 vol% and then decreased in 50 vol%. When comparing the predicted strength values with the experimental strength values at higher fiber loading, it can be identified that there is a large deviation, which may be due the structural defects occurred during the preparation of composite specimens. These structural defects may occur due to the formation of fiber agglomeration by higher fiber loading during processing. The Hirsch's model is predicting the tensile strength values above the experimental values, whereas the Series and MBB models are predicting the tensile strength values below the experimental values.

Figure 5b shows the comparison of the predicted and experimental tensile modulus for different fiber loadings. Here also, the Hirsch's model predicts the tensile modulus of the composite which is very close to the experimental tensile modulus values compared to the other two models. It predicts the tensile modulus values above the experimental values. The Series and MBB models predict the tensile modulus values below the experimental values.



(a) (b)

Figure 5. Comparison of experimental tensile modulus and strength values with theoretically predicted result values at different fiber loading: (a) tensile strength and (b) tensile modulus.

4. CONCLUSION

The effects of fiber length and loading on the mechanical properties of the randomly oriented CGF/PF composite were investigated and compared. Increasing the fiber loading at all fiber length composites, the tensile and flexural property values and also impact strength values increased. In the case of composites with the fiber length of 3 and 9 mm, the maximum mechanical properties were obtained at 40 vol% of the CGFs. But, in the case of composites having the fiber length of 15 mm, the tensile and flexural properties were reached the maximum level at 30 vol%, whereas the impact strength reaches the maximum value at 40 vol%. When comparing the mechanical properties at all the cases, the composites having the fiber length of 9 mm give the highest level of mechanical properties. Therefore, it can identify that 40 vol% and 9 mm of the CGF is designated as the optimum fiber loading and the critical fiber length to obtain the better mechanical properties in this combination. Even though the 40 vol% composite gives the highest level of mechanical properties, the crack propagation and extension, fiber pull-out and the breakage of the fiber during the load sharing are observed through the micro-structures of fractured surface the composite specimens using SEM. The mechanical properties of CGFs and their composites are comparable with the banana and roselle fiber composites. The experimental tensile property values were compared with the theoretically predicted values and found to be in good agreement. Finally, it can be concluded that the incorporation of the CGFs has improved the mechanical properties of the PF composites. Therefore, the CGFs were proved that they are a good reinforcement candidate for the phenol formaldehyde resin matrix.

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DOI : 10.24297/jac.v13i11.5910